VTT Technical Research Centre of Finland

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Kutila, Matti; Kauvo, Kimmo; Aalto, Petri; Garrido Martinez, Victor; Niemi, Markku; Zheng, Yinxiang

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Matti Kutila
VTT Technical Research Center of Finland Ltd.
Tampere, Finland
matti.kutila@vtt.fi

Kimmo Kauvo
VTT Technical Research Center of Finland Ltd.
Tampere, Finland
kimmo.kauvo@vtt.fi

Petri Aalto
Nokia
Tampere, Finland
petri.aalto@nokia.com

Victor Garrido Martinez
BMW Group Research, New Technologies, Innovations
Munich, Germany
Victor.Garrido-Martinez@bmw.de

Markku Niemi
Business Tampere
Tampere, Finland
markku.niemi@businesstampere.com

Yinxiang Zheng
China Mobile Research Institute, CMCC,
Beiing, CHINA
zhengyinxiang@chinamobile.com

***Abstract*—This article discusses the results of supporting transition towards fully automated driving with remote operator support via the novel V2X channels. Automated passenger cars are equipped with multiple sensors (radars, cameras, LiDARs, inertia, GNSS, etc.), the operation of which is limited by weather, detection range, processing power and resolution. The study explores the use of a dedicated network for supporting automated driving needs. The MEC server latencies and bandwidths are compared between the Tampere, Finland test network and studies conducted in China to support remote passenger car operation. In China the main aim is to evaluate the network latencies in different communication planes, whereas the European focus is more on associated driving applications, thus making the two studies mutually complementary.**

5G revolutionizes connected driving, providing new avenues due to having lower and less latency variation and higher bandwidths. However, due to higher operating frequencies, network coverage is a challenge and one base station is limited to a few hundred meters and thus they deployed mainly to cities with a high population density. Therefore, the transport solutions are lacking so-called C-V2X (one form of 5G RAT) to enable data exchanges between vehicles (V2V) and also between vehicles and the digital infrastructure (V2I). The results of this study indicate that new edge-computing services do not cause a significant increase in latencies (< 100 ms), but that latency variation (11 - 192 ms) remains a problem in the first new network configurations.

Keywords—V2X, automated driving, vehicles, 5G, latency

I. Introduction

Automated driving is the mega-trend which will change the mobility habit and also automated passenger cars significantly within the next 10 years. More and more decision making of cars in different situations is handled by algorithms programmed into the vehicles, instead of the human driver. However, traffic is a complex environment and it is very unlikely that all different possible incidences can be pre-programmed to passenger cars in advance. Many rare events still need remote recovery support from the operation centre. In many cases, the remote operation centre also needs complementary data from vehicles and edge-computing units in order for fail-safe transition between manual and automated driving modes to be activated.

Typical development needs from the automotive industry are related to availability of networks and interoperability of communication equipment. The high bandwidth requirement is due to the fact that in the future, the first automated driving functions will need supervision, and even sharing the Light Detection and Ranging (LiDAR) and camera data with remote operation centres is mandatory feature. The cost needs to be reasonable, presenting challenges for roaming charges [10]. The 5.9 GHz (5875-5905 MHz) band has been allocated to the transport industry for V2X safety related applications [2]. There have been two compelling technologies, C-V2X (taking care of 3GPP) and ITS G5 based on IEEE 802.11p. Thus, C-V2X is a cellular based approach whereas ITS G5 is a WiFi solution. Nevertheless, the application layer and message standards are mainly similar, which helps the application developers introduce new services and ignore the communication channel. The main organisations pushing automotive 5G and C-V2X standards forward are 5GAA, 3GPP and ETSI, all having their own role whether in communication protocols or message formats [9]. The standardisation has taken huge steps during the last 10 years and one problem is that part of the official and de-facto standards are contradictory, thus impairing common implementation.

5G networks bring several key improvements compared to 4G networks. In the remote operations field, the most important of these features is the reduced latency in the radio access network (RAN). Remote operations also require that the reliability of the network is at a very high level. Combining these requirements has led to the development of an ultra-reliable low-latency communications (URLLC) feature in the 5G technology. This feature is implemented in the 5G networks as a part of the stand-alone (SA) 5G that takes the reliability target of LTE in terms of block error rate from 10-2 to 10-5 (or even up to 10-9) in 5G. Latency wise, SA 5G will reduce the latency of 4G in the order of tens of milliseconds down to just milliseconds. In addition to the increased reliability and lower latency, 5G brings an increased throughput as compared to LTE, with peak rates in the downlink reaching already a few Gbps.

Applications and services that require wide bandwidth, increased network throughput and reduced network latency are challenging for LTE and WiFi networks [3]. With the Mobile Edge Computing (MEC) solution, mobile operators and enterprises can address these challenges by hosting the content, services and applications at the edge of the network. Mobile Edge Computing (MEC) 3GPP LTE System architecture defines the User Plane (UP) functions separated from the Control Plane (CP) functions to allow UPs independent scalability, evolution and flexible deployment. The MEC introduces applications to the edge of the network with the following benefits:

- Real-time: Lowest end-to-end application latency.
- Private: Local communications to private networks for performance, privacy and security.
- Analytical: Real time insights from data are exploited at the point of capture; minimum bandwidth required for data entering into service application.

The S1-Local Break Out offload to applications at the edge can be based on the transparent insertion or so called ”bump-in-the-wire” architecture.

II. TEST SCENARIOS

The 5G-DRIVE European trial scenarios are based on implementing modern communication and edge-computing systems to infrastructure and validating necessary performance for supporting automated driving. The scenarios address the aggregation of fleet data via MQTT edge computing and storing data to the cloud. Emara, et. al. [8] reported that MEC can improve the network performance up to 80 %, since all the information is not delivered to the cloud and thus occupies the communication channels.

With its partners, China Mobile has been participating in Ministry of Industry and Information Technology (MIIT), he Ministry of Transport of the People's Republic of China (MOT), National Development and Reform Commission (NDRC's) Intelligent Connected Vehicle, Intelligent Roads and related demonstration projects in Beijing, Wuxi, and other cities. With the support of MIIT, MPS and the Jiangsu Provincial Government, 7 core members joined V2X industry partners to build the Wuxi C-V2X city-level demonstration application project. The project has built the world's largest urban-level C-V2X network to date. More than 40 items of data were exchanged, achieving 40+ V2X application scenarios, improving the travel experience, improving the level of urban intelligent traffic management and leading to the development of global V2X technology and industry.

Overall, the following scenarios are considered as the test cases in this experimental study [4]:

- *Uplink bandwidth capacity*
- *Inter-operability between different mobile network band frequencies (5G and 5.9 GHz)*
- *Mobile edge computing*
- *Message formats - Basic Safety Message (BSM) in China and Cooperative Awareness Messages (CAM) in Europe*
- *Latency times*

5G-DRIVE is intended to measure the crucial KPIs (see TABLE I.) and generate conclusions concerning how they support future connected driving scenarios. The Chinese twinning project KPIs are listed in TABLE II. The trials conducted in the parallel China project are more network-orientated whereas the European ones deal with V2X application specific scenarios. The trials have been tailored to ensure comparison in the GLOSA and Intersection driving use cases between European and China trials. Main differences are that in China the trials are LTE network based whereas the European ones are done with PC5 devices but also relying on LTE network. The other distinction is that European V2X applications use Decentralized Environmental Notification Message (DENM) message format whereas in China side BSM type of messages are used.

TABLE I. KPIS IN EUROPEAN TIRALS

Scenario	KPI title	Metrics
GLOSA APPLICATION		
MEC - MAP		
	Latency	< 5 s
	Packet Error rate	< 10 %
MEC - SPaT		
	Latency	< 2 s
	Packet Error rate	< 10 %
IoT MAO		
	Latency	< 10 s
	Packet Error rate	< 1 %
DAY 1 MESSAGES		
Low traffic - DEMN		
	Latency	< 10 ms
	Packet error rate	< 1 %
	Active stations	100
GLOSA		
	Channel load	150 000 b/s
AUTOMATED DRIVING		
bandwidth - CPM		
	Packet error rate	< 10 %
	Latency	< 100 ms
	Channel load	> 1 620 000 B/s
bandwidth - MCM		
	Packet error rate	< 1 %
	Latency	< 100 ms
	Channel load	> 1 120 000 B/s

TABLE II. KPIS IN CHINESE TIRALS

Scenario	KPI title	Metrics
LTE based KPIs		
ACCESSIBILITY		
	UE attach success rate (SR)	> 95 %
	Radio Resource Control (RRC) connection setup SR	> 95 %
	Paging SR	> 95 %
	Call drop rate	< 5 %
MOBILITY		
	Handover (HO) SR	> 95 %
	HO latency data plane (DP)	60 ms
	HO latency control plane (CP)	40 ms
INTEGRITY		
	CP latency	100 ms
	DP latency	30 ms
LTE optimization KPIs in commercial networks		
COVERAGE		

	Reference Signal Received Power (RSRP)	> -100 dBm
	Signal-to-Interference-plus-Noise Ratio (SINR)	> -3 dB
	City coverage	> 95 %
	Rural coverage	> 92 %
ACCESSABILITY		
	RRC reconnection ratio	< 5 %
	VoLTE success ratio (QCI1)	> 99 %
	Single Radio Voice Call Continuity (SRVCC) HO ratio	< 0,2 %
	VolLTE call drop rate	< 1 %
LTE general KPIs in commercial networks		
	DL average rate	35 Mbps
	UL average rate	6-7 Mbps
	Outdoor DL rate at edge	5 Mbps
	CDF 5 % RSRP at edge	-105 dBm
	CDF 5 % SINR at edge	0 dB
	CDF 50 % RSRP	-90 dBm
	CDF 50 % SINR at edge	13 dB
GLOSA APPLICATION		
BSM		
	Latency	< 100ms
	Packet Error rate	< 10 %
SPaT		
	Latency	< 100ms
	Packet Error rate	< 10 %
MAP		
	Latency	< 100ms
	Packet Error rate	< 10 %

The intersection driving is one of the major use cases in which C-V2X technologies support automated driving functions. There are two aspects to consider when sharing high-definition (HD) maps and sending status messages from one car to another. The communication range is expected to be at least 100 m [5]. Hobert et al. [1] investigated different automotive applications in which the standardised message and vehicle networks can be used for improving cooperative automated driving. V2X was seen as the key enabling technology for improving vehicle situation awareness.

There are various bands dedicated for connected and automated driving. The band allocation depends on operators' permissions to use them. For C-V2X and ITS G5 applications, the spectrum of 5855 – 5925 MHz has been allocated whereas the main 5G channels are the cellular mobile frequency bands (e.g. 800, 900, 1800, 2100 and 2600 MHz) and new allocated bands (e.g. 700 and 3400-3800 MHz) [6]. Campolo, et al. [7] reported that reasonable CAM package transmission frequency is between 50-100 ms in order to keep packet loss reasonable. However, the optimal parameters also depend on communication distance and available bandwidth (typically 10 - 20 MHz).

eLvira is an automated passenger car designed for operating both in fully automated and remotely operated mode (see Fig 1, Fig 2 and Fig 3). The car is equipped with modern sensors which are expected to be introduced in future automated driving scenarios including LiDARs, radar and cameras to supervise 360 deg. around the car. It is also equipped with short- and long-range communications (LTE-A Pro, C-V2X and 5G modems). The demo car is programmed to work like existing automated passenger cars today in real traffic; they cease operation when the weather conditions reduce visibility.

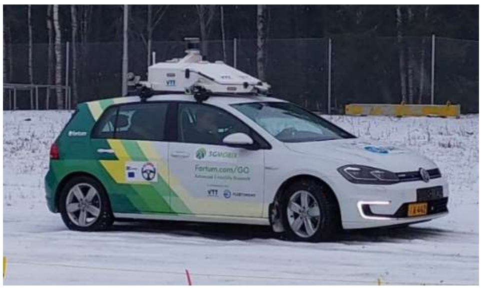

Fig 1. eLvira remotely operated and automated passenger car used in the European V2X trials.

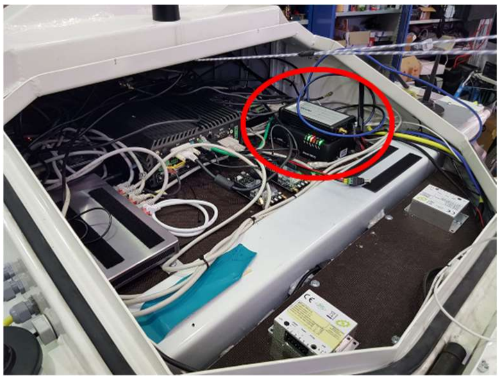

Fig 2.On-Board Unit (OBU) in eLvira test vehicle.

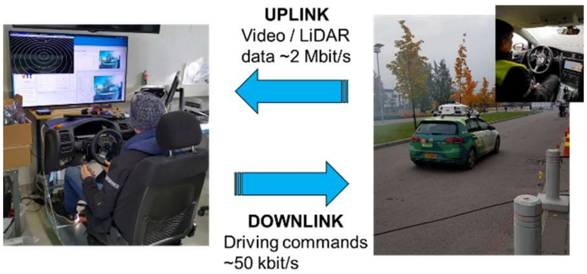

Fig 3. eLvira remotely operated and automated passenger car for V2X trials.

III. TEST ARRANGEMENTS

The Hervanta test network utilizes E-UTRA Band 38, or 2600 MHz, as the frequency band for the RAN. The network has its own evolved packet core (EPC) within Tampere to enable low latencies in the backhaul due to short distances between the Radio Access Networks (RAN) and Evolved Packet Core (EPC). The actual RAN optimization capabilities enable testing of V2X use cases in the network with features that commercial mobile network operators have not yet taken into use.

The measurement tools were installed to the eLvira automated car to demonstrate feasibility and challenges when using the Pre-5G network. Performance of the Tampere test network was measured using VTT's test vehicle. Measurements were made at low speeds (<25 km/h). The vehicle router used was a Sierra Wireless MP70 LTE-A. VTT's own tailored software was used to measure latencies and bandwidth in the test site. The main use case adopted by the project is to support automated driving through connected intersections. The use case Green Light Optimisation Speed Advisory (GLOSA) and intersection safety awareness can be improved with modern communication technologies (e.g. 5G or C-V2X). The aim is to experiment network performance to serve also video data transmission in future for vehicle remote operation purposes. The problem in intersections is visualised in Fig 4, where the car without connectivity is not avoiding the pedestrian in the pedestrian zone. On the other hand, the automated passenger car sensors cannot see the pedestrian on time without infrastructure support. In this case the low latency networks are needed for accident avoidance.

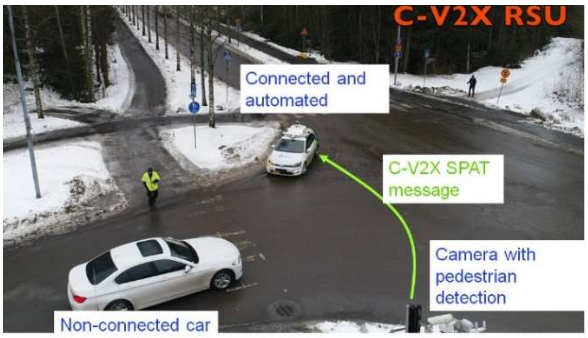

Fig 4. eLvira remotely operated and automated passenger car for V2X trials. One of the key targets is to enable low latency intersection driving support functionality where RSU and connected vehicles can cover all blind spots.

For the V2X trail, an RSU (Road Side Unit) is assembled on the lamp post (See Fig. 2) at each crossroad in the Chinese trial site. The OBUs are placed in the test car. OBU and RSU can transmit and receive the V2X messages through PC5 connection and Uu connection. The experiments are supporting situation awareness of automated vehicles with delivering BSM messages for the passing cars.

Fig 5. RSU components used in the V2X trials in China twinning project. The message exchange benefits between RSU and in-vehicle OBUs are the trial goals.

Fig 6. OBU for V2X trials in China which are connected to the roadside equipment..

IV. Experiments

The Tampere Smart City testing network depicted in Fig 7 L1 has been built in cooperation with Nokia Oyj and the City of Tampere to enable future Smart City services. The network consists of eight Nokia Flexi Zone eMBB base stations and an MEC Edge computing server. There is an optical fibre connection from each base station to the MEC server. Base stations are attached to the street light poles.

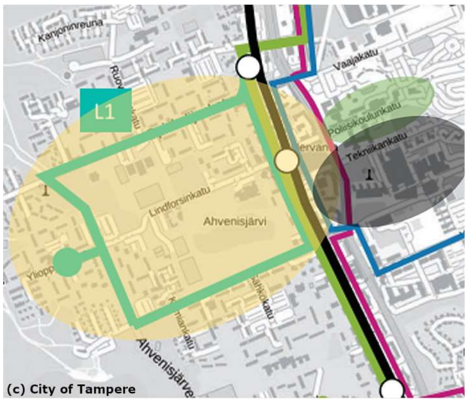

Fig 7. Tampere L1 test area used in the European tests. The area is square which dimensions are about 2,5 x 2,5 km.

A) Signal quality

Various signal quality parameters were stored into log files during the test drive. For further examination, the Reference Signals Received Power (RSRP) values were selected. Fig 8 depicts both the locations of the eNB base stations and the RSRP values > -90dBm. Colour coding depicts connection and handover to a base station. The results show that the antenna direction is not optimal when compared to the original plan, where excellent or good RSRP values should cover all the yellow area L1 in Fig 7. Fig 9 presents the RSRP plot categorized as excellent - good - fair; this also shows that only a small portion of the route has an excellent signal level.

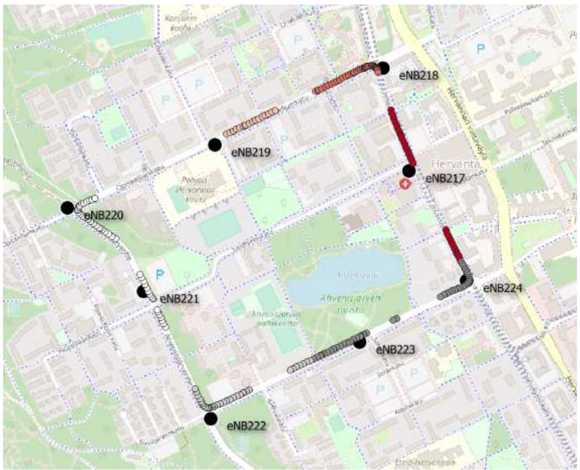

Fig 8. eNB locations and RSRP > -90dBm in European test site. There are 9 base-stations in the area.

In the Chinese trials, from the V2X applications such as GLOSA in V2X trials, the performance of the LTE network was evaluated by making measurements using On-Board Units (OBU) and Road Side Units (RSU). The performance of V2I services such as Green Light Optimized Speed Advisory (GLOSA) application meets the requirement for both Uu connection and PC5 connection. The latency is less than 100 ms and the packet error rate is less than 10%.

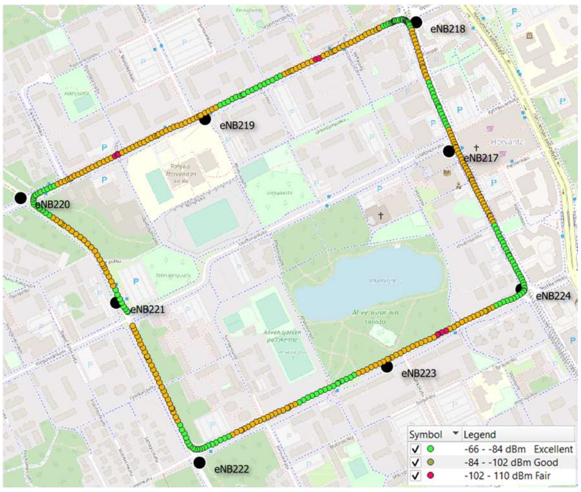

Fig 9. RSRP measurements. Green means very good signal strength whereas red refers to weak signal.

B) *Latency measurements*

During the tests conducted, latencies in two network communication steps were measured, see Fig 10. One step was directly in OBU without running any MEC or MQTT services. The first ones were measured when MEC was added and the second ones when the MQTT service was turned on.

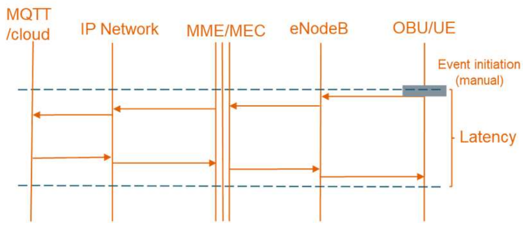

Fig 10. Message sequence diagram in the tests

The results are presented in Fig 11, Fig 12 and Fig 13, showing the whole test track network latency performance values in milliseconds. The aim is to experiment the latencies when the connected driving support system is running in edge instead of cloud for optimising the processing power and latencies needed in different scenarios (e.g. intersection). There is one corner (50 meters long) where the connection was lost, and there the results have been ignored in the calculations.

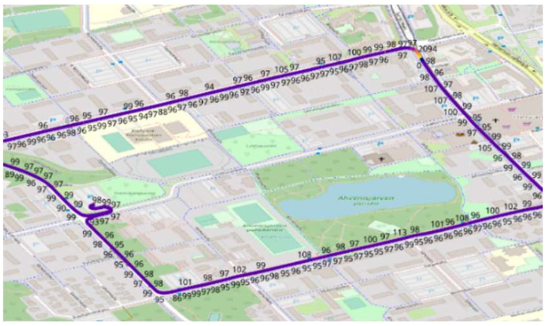

Fig 11. The L1 test field latencies without MEC service in between. Data from the network directly to the cloud service. Latencies are varying depending on measurement points due to handover between base-station and line-of-sight obstacles.

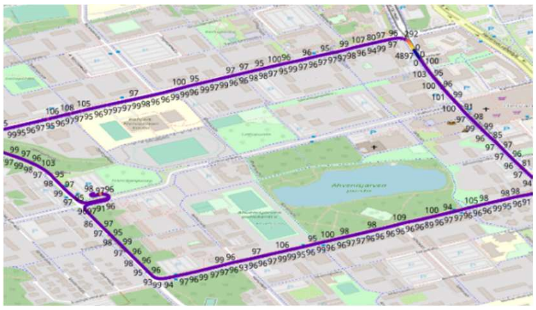

Fig 12. Latencies measured in the local MEC service in the L1 test field

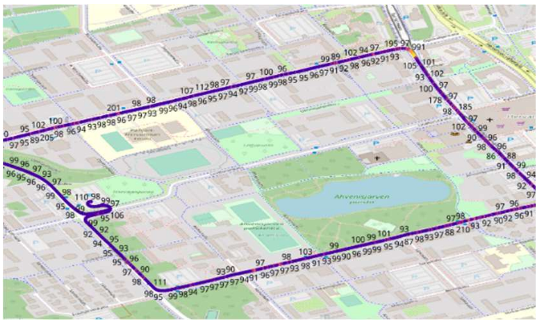

Fig 13. Latencies when implementing both MEC service and cloud-based service via MQTT interface

The influence of MEC services on network latencies is not significant. Median latencies remain, even if MEC services are running. This is as expected, since MEC and also the cloud-based MQTT services are connected using optical fibres.

- MQTT cloud: 99 ms
- MEC service: 99 ms
- both MQTT and MEC used: 99 ms

However, the standard deviation depends on network configuration, and the additional components (MEC and MQTT) cause additional overheads to the measurements.

- MQTT cloud: 11.1 ms
- MEC service: 30.9 ms
- both MQTT and MEC used: 192.1 ms

Thus, the main challenge is the increased variation which additional components in the network cause, even if the median communication remains in a reasonable tolerance range. For automated driving purposes, 99 ms is sufficient when considering urban area speed, which is normally less than 50 km/h.

V. Discussion

The City of Tampere aims to be among the leading cities in terms of technical development. Key focus areas are smart traffic solutions and automated driving. Tampere aims to introduce robot buses gradually during 2021. The aim is to support feeder transportation to the new tram line currently being constructed. Automated driving sets new requirements both for physical and digital infrastructure. The test network helps to understand these requirements in more detail and provides possibilities to gain practical experience from a test area located among real city infrastructure -- this is globally quite novel. One of the new avenues is a kind of hybrid communication in which available vehicle-to-network (V2N) and vehicle-to-vehicle (V2V) channels are optimised according to message priorities. C-V2X is one of the 5G evolution paths which enables vehicles and infrastructure components to exchange information directly without network overheads. However, access to the cloud is also useful and therefore, basically different types of radio access technologies (RATs) are needed depending on the application. Today, C-V2X 5G Release 14 enables warnings and short messages to be distributed, whereas Release-16 is expected to make trajectory and sensor data sharing features available, thus taking passenger car interaction to a new level [11].

Comparing the results of the China field test and the European done in Finland is not straightforward since the target of both implementations are not aligned. The Chinese twinning project is led by China Mobile, which is a Mobile Network Operator (MNO) looking for business opportunities in future traffic which will be more connected and automated. The important aspect for the MNO is to ensure that latencies in different network planes remain within reasonable limits (< 40 ms), since data processing represents a major part of the V2X message exchange. The European project focuses more on the full communication chain from ITS services to the end user ECU. The reasonable expectation is that latencies will always remain below 2000 ms and rather less than 250 ms. Thus, these measurements between China and Europe are more complementary than directly comparable. This is advantageous, since both sides create added value to understand the connectivity requirements for different ITS components.

VI. CONCLUSION

This article compared the aims of bringing new 5G based C-V2X networks to the market to make automated driving functions and remote diagnostics available. Even though this article is focused on infrastructure supported automated driving, the low latency features also support remote diagnostics enabling the deployment of automated driving function to the market. The results are mostly related to the 5G-DRIVE-EU and 5G Large-Scale Trial-China twinning projects. The 5G Large-Scale Trial is more MNO oriented and is dedicated to investigate which types of equipment are needed to support the transition to 5G supported C-V2X. The RSUs have been installed and latencies will be measured in different network planes. However, the applications correlated with European trials including GLOSA and intersection driving scenarios will be compared. The first results indicate very low U-plane latencies (4-10 ms) [12].

The results in the European test network include access to the network, a mobile-edge-computing unit (MEC) and the cloud service side with MQTT interface. The results indicate that network strength depends on line-of-sight access due to higher frequencies, which is challenging in real traffic where trees, buildings and other vehicles obscure base station antennas. The other major result is that the highest latency is due to communication with the network (C-plane), which aligns with the results of the Chinese twinning projects. The measured latencies vary from 80 - 130 ms and the MEC and MQTT-cloud did not have much impact on latencies, although they caused a clear increase in latency variation (11 ms => 192 ms) which remains a problem for remote vehicle operations but is suitable for many V2X support functions (e.g. situation awareness) which are not safety critical.

As a concluding remark, even if the currently available test network modems are LTE-based and the new radio (NR) is not expected before 2022, the special test networks and more precise understanding of the needed new features are crucial to avoid unnecessary investments. 5G is more versatile and multi-functional, thanks to technologies such as slicing, Enhanced Mobile Broadband (eMMB) and Ultra-reliable low-latency communication (uRLLC). The problem for network investors is becoming very challenging, since 5G features are evolving rapidly and there are new releases of the standard every second year. On the other hand, the new features enable sharing computation power and sensor data between connected and automated passenger cars, which not only increases safety but also brings full automation closer to market entry.

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